Orbital Space Settlement Radiation Shielding

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Abstract

We examine the radiation shielding requirements for protecting the inhabitants of space settlements located in orbit. In particular, we recommend a threshold of 20 mSv[1]/year for the general population and 6.6 mGy[1]/year for pregnant women based on the most relevant existing standards and background radiation on Earth. With these thresholds we discover that space settlements in equatorial LEO (Low Earth Orbit) below about 500 km are likely to meet this standard with no dedicated radiation shielding. This reduces the mass of typical orbital space settlement designs by well over 90%.

Space settlement studies in the 1970s assumed that lunar regolith with a mass equivalent to Earth's atmosphere above high altitude cities, roughly 4.5 tons per square meter of hull, would be sufficient to meet a 5 mSv/year threshold for settlers at the Earth-Moon L5 point, their recommended settlement location. Using OLTARIS, NASA's online radiation computational tool, we found this to be far too little shielding for their 5 mSv/year threshold. Even at our higher thresholds about 10 tons/m^2 of lunar regolith is required.

Fortunately, radiation shielding mass requirements can be substantially reduced by using better materials and/or by placing settlements in low Earth orbit (LEO) rather than above the Van Allen belts. Specifically, to meet the 20 mSv/year and 6.6 mGy/year thresholds our calculations suggest that 6-7 tons of water or polyethylene radiation shielding per square meter of hull is sufficient in free space; and settlements in a circular 500 km or lower equatorial Earth orbit may require no shielding at all. The 1970s studies assumed extraterrestrial materials would be necessary to avoid launching enormous quantities of radiation shielding from Earth. If no radiation shielding is necessary, besides being far less massive, the first settlements may not need extraterrestrial mining and processing. This suggests a smaller step between large LEO space stations and hotels and the first settlements.

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[1] The modern measure of radiation is the Gray. The biological effect of a given level of radiation is measured in Sieverts. Conversion of Grays to Sieverts depends not only on the type of radiation involved but on the tissue being exposed. mSv stands for milli-Sievert, or one thousandth of a Sievert. mGy stands for milli-Gray, or one thousandth of a Gray. When converting from mSv to mGy, the mGy figure is always larger than the mSv for the same point. Note that in the radiation tables in this paper the mSv and mGy levels are 'measured' at different points.

It is important to note that there are significant uncertainties in our understanding of the effects of low-level continuous high-energy particle radiation on human tissue that need to be resolved. Also, this paper is based on numerical calculations, not physical measurements. A mission to validate the model radiation levels in equatorial LEO might be worthwhile.

Introduction

This paper examines the radiation protection requirements for permanent human settlements in orbit. By our definition a space settlement is a place where, among other things, children are raised, as opposed to a space station which is more of a work camp where people go for limited periods of time for specific purposes. A series of studies in the 1970s [Johnson 1975, O'Neill 1977] suggested the feasibility of building large orbital space settlements suitable for permanent habitation including raising children. One of the system drivers was radiation, as the location chosen was the Earth-Moon L5 point, a point equidistant from Earth and the Moon and well above the Van Allen belts. Thus, for these studies, the Earth's magnetic field provided no radiation protection.

Radiation levels in space are significantly higher than on Earth and this can have a number of negative effects on the human body including but not limited to birth defects, cancer, cardiovascular problems, central nervous system problems, cataracts and, particularly important, premature sterility [Straume 2010].

This radiation can be blocked either by shielding materials or by electromagnetic forces. The 1970s studies chose materials, and the mass of the resulting settlement designs is dominated by radiation shielding: 4.5 tons of lunar regolith per square meter of hull. This was intended to duplicate the radiation protection provided by the Earth's atmosphere, which is 10 tons/m^2 at sea level and about 5 tons/m^2 at high altitude cities. This shielding mass is far more than the structural mass, atmosphere, and interior accommodations combined. Thus, acquiring radiation shielding mass was considered one of the most difficult technical challenges in developing orbital space settlements. This drove the choice of L5 as the settlement location so that lunar materials could be used for radiation shielding. An elaborate transportation system was designed to deliver large quantities of lunar regolith to L5. It should be noted that L5 is well above the protective effects of Earth's magnetosphere, and the 4.5 tons of lunar regolith turns out to be insufficient as it is not a very good shielding material (see below).

Since the 1970s there has been considerable improvement in our understanding of radiation in space and ways to reduce the impacts of that radiation, but most of the long term studies have focused on voyages to Mars, not settlement [e.g., Wilson 1997, Cucinotta 2012]. These studies have assumed a few years of exposure, minimal spacecraft mass as the vehicle must travel to Mars, and only adults on board. By contrast, settlement involves decades of exposure, the potential for significantly more radiation shielding mass as the settlement generally isn't changing orbit, and children and pregnant women on board.

There is one study by Straume et. al. that examines radiation shielding requirements for Mars settlement [Straume 2010]. However, unlike orbit, Mars has ample materials for radiation shielding on the surface so the focus is on transit of settlers to Mars, which is on the order of a half year. Staume's study examined the limiting threat, i.e., what is the most serious risk that, if one has enough shielding to reduce that risk to acceptable levels, all other threats will be taken care of.

Studies of non-human primates found that oocytes[2] are extremely radiosensitive during gestation. At high radiation levels we expect an effective early onset of infertility. Oocytes are not replenished during a woman's lifetime and there are a limited number of them, all present at birth. As a result, in our study, we looked at radiation damage to female ovaries and assumed that if these can be kept healthy then radiation to other organs and tissue will be acceptable. We also look at the radiation threat to the developing embryo and fetus during pregnancy and assume that acceptable levels here are also acceptable for children.

Radiation in Space

There are three major classes of dangerous radiation in space [Schimmerling][Clement 2012]:

The first class is caused by solar storms. These happen 5 to 10 times per year, except near a solar minimum [Cucinotta 2012]. These storms are directional, going outward from the Sun in a relatively small area, last for several hours at peak exposure rates, and are dominated by protons with an energy of one MeV up to a few hundred MeV. Fortunately, protons have small mass (comparatively) and are relatively easily blocked. Severe storms, however, may require extra shielding for short periods of time. Also, dangerous solar storms are very rare. Only five since 1955 have been strong enough to endanger astronaut health when protected by normal spacecraft shielding [Clement 2012].

The second class of dangerous radiation consists of galactic cosmic rays (GCR). If these are adequately shielded, then solar storms will cause few problems. GCR are made up primarily of nuclei with no electrons, can travel at relativistic speeds, and are omni-directional. Energy varies from less than one MeV/u[3] to more than 10,000 MeV/u with a median of perhaps 1,000 MeV/u. The level of GCR in the solar system varies with the solar cycle, with periods of low magnetic activity allowing more GCR into the inner solar system, but this effect is limited to energies less than roughly 2,000 MeV/u [Cucinotta 2012]. While most of the nuclei involved have low atomic number, the most dangerous of the GCR particles are heavy ions such as iron nuclei. Fortunately, GCR is at a fairly low level.

There is a third class of space radiation which is relevant to settlements in Low Earth Orbit (LEO). This consists of trapped electrons and protons in the Van Allen belts [Schimmerling] which can result in somewhat high radiation levels in relatively low Earth orbit (very roughly 1,000 - 60,000 km). However, these are light particles (electrons and protons) that can be

[2] The cells that develop into eggs.
[3] MeV/u stands for million electron volts per neutron or proton.

stopped by minimal shielding, such as the settlement hull. This radiation can cause problems for settlers performing spacewalks for repairs or recreation.

Unfortunately, much of what we know about radiation effects on the human body come from studies of the victims of the Hiroshima and Nagasaki atomic bomb attacks, which involved very high radiation levels for short periods of time, which doesn't necessarily generalize to long term exposure to low level GCR. There have also been a number of studies of people exposed to radiation at work, e.g., nuclear power plant operators. These indicate a possible small effect on fertility in both men and women [Straube 1995, Doyle 2001]. In a survey paper, Brent found that to negatively affect pregnancy and fetal DNA, a fairly high radiation level is required, well above our proposed 20 mSv/year and 6.6 mGy/year thresholds [Brent 2012]. However, these studies do not involve the high energy massive particles that characterize the most dangerous parts of GCR.

Radiation studies on animals are usually limited to short time periods because that is easier to do. Short periods of higher flux are used to simulate lower levels for longer periods. So, due to the nature of the data, relatively little is known about the biological effect of long periods of low-level high-energy high-mass particles such as relativistic iron nuclei. Thus, the conversion of GCR radiation levels (which can be easily measured) to biological effectiveness must be viewed with suspicion; improved data and understanding may affect the results presented here.

The problem is further confused by secondary particles. When an iron nucleus (or other heavy particle) passes through a material and strikes another nucleus, a shower of smaller secondary particles is created. These can be more damaging than the original particle, just as a shotgun wound can be more serious than a wound from a rifle bullet. Thus, a small amount of shielding can worsen radiation damage by creating secondaries, so shielding must be thick enough to absorb most of the secondaries as well.

For the purpose of this paper, we hypothesize that if settlement radiation shielding is sufficient to keep GCR damage of human ovaries prenatally to an acceptable level then all other sources of space radiation for all other tissues will be acceptable, except for the embryo and fetus. We quantify this level with OLTARIS, NASA's web front end to sophisticated radiation modelling software [OLTARIS 2011, OLTARIS 2014].

Radiation Threshold for Space Settlement

The amount of shielding thought necessary to protect settlers from the space radiation environment depends heavily on the threshold chosen. We have chosen 20 mSv/year for the general population, with caveats, to match the most relevant data points (see next paragraph), and 6.6 mGy/year for pregnant women. This is well above the 5 mSv/year used in the 1970s studies, which is, in our opinion, unnecessarily low. The 20 mSv threshold is well below the limit

for deterministic radiation effects[4], 500-2,000 mGy [Clement 2012] (depending on the tissue) and is intended to limit stochastic effects such as cancer.

We first examine the 20 mSv/year limit for the general population followed by a discussion of the 6.6 mGy/year limit for pregnant women.

The International Commission on Radiological Protection (ICRP) recommends a 20 mSv limit for occupational radiation exposure [Wrixon 2008]. The threshold used by the Japanese government to determine which residences may be re-occupied after evacuations due to the Fukushima nuclear power plant accident is also 20 mSv/year [McKirdy 2014]. 50 mSv/year is the threshold for radiation workers in the U.S. [Space Radiation Analysis Group 2014]. The annual limit for US astronauts is 500 mSv/year in the blood forming organs with a lifetime cap of 10,000 - 30,000 mSv for women and a higher limit for men [Space Radiation Analysis Group 2014].

20 mSv/year is considerably above the average background radiation in the U.S., 3.1 mSv/year (not including medical X-rays, etc.) [Linnea 2010, NRC 2010]. However, this is an average, and much higher levels exist locally. There are several large regions of Europe, particularly in Spain and Finland, with levels over 10 mSv [World Nuclear Association 2014] and there are inhabited parts of the world with much higher levels with no known major negative effects.

For example, the highest recorded background radiation on Earth is in Ramsar, Iran, where monitored individuals have received an annual dose up to 132 mGy/year, far above our 20 mSv/year threshold [Ghiassi-nej 2002][5]. Other high natural radiation areas include Yangjiang, China, Kerala, India, and Guarapari, Brazil, with no apparent major negative effects. Thus, it seems that 20 mSv/year is a reasonable level to use for the present study, being aware that additional research is needed and this threshold may need to be changed as better data and theory become available.

There is some reason to believe that the radiation threshold should be lower for the embryo and fetus. For example, [Wrixon 2008] recommends a 1 mSv limit for pregnant women with occupational radiation exposure and [Valentine 2000] recommends 1 mGy. This is in addition to the background radiation, which can be much higher than the 20 mSv limit we propose. Note that the ICRP does not recommend pregnancy termination at fetal exposures less than 100 mGy from medical sources [Valentine 2000].

The ICRP has developed guidelines for acceptable radiation levels for (among other things) embryo and fetus. An ICRP publication [Wrixon 2008] established radiation thresholds based

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[4] A deterministic radiation effect is one that will almost certainly happen soon, as opposed to stochastic effects such as contracting cancer years later.

[5] For a given level measured in Grays the value in Sieverts is as great or greater at a given point, depending on the tissue in question. Note that in the tables below this appears to be violated because the measurement are done at different points.

on [Valentine 2000] and [Valentine 2003] for various radiation threats to the fetus and embryo and published these values as indicating the dose at which problems have been observed:

	[Wrixon 2008]
Effect	mGy threshold
Pre-implantation lethality	100
Introduction of malformations	100
Severe mental retardation	300
Negative effects on IQ	100
Life-time cancer risk 3x increase	100

Table 1. The rows list possible effects of radiation exposure before birth. The [Wrixon 2008] numbers are a summary of radiation thresholds for pregnant women as part of recommendations for radiation dose, which is very relevant to medical decisions for pregnant women (e.g., whether to have an x-ray or not). For humans, there is no clear data on prenatal radiation exposure to high energy particles, at least for mental effects [Valentine 2003].

Notice that the values given here are in mGy, a measure of radiation, not mSv, a measure of biological effect. This is because there is presently no meaningful way to judge the correctness of the tissue-weighting factors used to convert radiation (in mGy) to biological effect (in mSv) [Valentine 2003].

All this suggests that it might be wise to keep prenatal exposure to significantly less than 100 mGy over nine months. We suggest a factor of 20 less, or 5 mGy per nine month pregnancy, which translates to about 6.6 mGy/year. This should not be considered definitive. Indeed, there is little evidence for negative effects below the values in Table 1 much less for 20x less. Note that if this level is exceeded by a small amount, additional shielding could be temporarily added to the homes of pregnant women to meet the threshold.

We assume that the combination of thresholds for ovaries and the fetus will be protective for children as well. This will require an animal research program to verify.

It should also be noted that there is some evidence that low levels of radiation stimulate an adaptive response from the human body that reduces the radiation damage one might otherwise expect [Ghiassi-nej 2002]. There are similar results for rodents in some circumstances [Valentine 2003]. This is hard to study and should not be considered definitive, but may make the low levels of GCR expected by space settlers more acceptable than we currently believe.

Clearly, people moving from Earth to a space settlement can expect to be exposed to higher levels of radiation, but this can also be true for people moving from place to place on Earth.

Radiation Shielding Materials

The best shielding materials for GCR are dominated by hydrogen. This is because heavy positively charged particles with a lot of energy are stopped primarily by electromagnetic interaction with electrons rather than collisions with nuclei [Ziegler 1988]. Indeed, as we have seen, collisions with shielding nuclei can increase effective radiation dose due to the creation of secondary particles. Large numbers of electrons are pulled out of position as a particle passes through the material, transferring energy from the particle and eventually bringing it to rest. Liquid hydrogen might be the ideal shielding material from this perspective, but it is difficult to handle and maintain. Among the best practical materials are polyethylene and water [Wilson 1997].

Polyethylene consists of long strands of carbon atoms each bonded to two hydrogen atoms (except at the ends). It is a little better than water because carbon nuclei are smaller than oxygen, making for fewer collisions and less mass for the same number of hydrogen atoms. Note that many asteroids are rich in carbon compounds and water.

Lunar regolith, which has little hydrogen, is a poor radiation shielding material. This is illustrated by Table 2 which shows the radiation level expected in “free space” (above the Van Allen belts in OLTARIS terminology), given the mass of the shielding and the type of material. Note that a much greater mass of lunar regolith is necessary to bring radiation levels below 20 mSv/year than with polyethylene or water.

	polyethylene		water		lunar regolith	
tons/m^2	mSv/yr	mGy/yr	mSv/yr	mGy/yr	mSv/yr	mGy/yr
1	193	85	199	86	274	109
2	136	52	146	54	261	82
3	90	31	100	34	221	62
4	57	18.5	66	21	172	48
5	35	10.8	42	12.5	126	37
6	20.9	6.3	26.3	7.5	89	28
7	12.2	3.6	16	4.4	61	20.9
8					40	15.1
9					26.1	10.5
10					16.6	7.1

Table 2: Comparison of shielding materials in free space. The rows indicate yearly radiation levels at a given shielding mass. The first column lists tons of shielding per square meter, the other columns list different materials and measures. The mGy columns are a measure of radiation taken inside a ball of shielding, the mSv columns are taken from the ovaries in a model of the human body inside a ball of shielding. The red color indicates that values are less than 20 mSv/year. Note that the 6.6 mGy/year level for pregnant women is also met (or nearly so for lunar regolith). Note also that polyethylene is a bit more effective than water, and both are quite a bit more effective than lunar regolith. All values are calculated by OLTARIS.

Location Influence on Radiation Shielding Requirement

The radiation experienced by space settlers depends a great deal on location. For example, on the surface of Mars or the Moon approximately 50% of the GCR is blocked by thousands of km of rock. Also, on Mars, there is some protection from the atmosphere, although not much. Furthermore, settlements can be located in caves or buried with local materials which are plentiful. Local materials can also be used by orbital space settlements when built co-orbiting with asteroids. This paper will focus on a strategy suitable for the first few space settlements: placing them in equatorial low Earth orbit (LEO) to take advantage of the Earth's magnetic field and the Earth itself.

Radiation levels in LEO are influenced by both the altitude of the orbit and the inclination. The lower a settlement is the more radiation protection it receives both from the Earth itself and from Earth's magnetic field. Very low inclinations, i.e., very close to 0, experience much less radiation due to the shape of the magnetic field. See Table 6 below.

Table 3 contains the yearly radiation levels calculated for five orbital altitudes (600, 700, 800, 900, and 1000 km) for circular equatorial orbits as a function of polyethylene shielding measured in tons of material per square meter of hull. Note that at 600 km one ton of shielding is more than adequate to meet the 20 mSv/year and 6.6 mGy/year limits. The shielding required to meet these limits rises with altitude as the Earth blocks less of the sky and the magnetic field weakens.

	600 km		700 km		800 km		900 km		1000 km	
tons/m^2	mSv	mGy	mSv	mGy	mSv	mGy	mSv	mGy	mSv	mGy
1	14.2	5.2	25	10	109	60	238	135	409	234
2	14.1	4.9	18	5.9	39	9.8	158	72	115	23.7
3	12.1	4.1	14	4.7	23	6.4	36	8.9	55	12.4
4	9.5	3.2	11	3.6	14.7	4.3	20	5.3	28	7
5	6.9	2.3	7.8	2.5	9.5	2.8	11.9	3.3	15.5	4.1

Table 3: Yearly radiation levels calculated for five orbital altitudes (600, 700, 800, 900, and 1000 km) for circular equatorial orbits in both mSv/year (human ovaries) and mGy/year (outside the body). Rows are for levels calculated for polyethylene shielding in tons per square meter of settlement hull. The columns are radiation levels at different altitudes and different measures. Red indicates that the level meets our 20 mSv/year and (in this case) 6.6 mGy/year thresholds. All calculations use OLTARIS.

Noting that at 600 km with a single ton of shielding the radiation expected, 14.2 mSv/year, is well under the 20 mSv/year limit, we did additional calculations at 500 and 600 km using very small amounts of shielding. The results are in Table 4:

shielding	500 km		600 km	
tons/m^2	mSv/yr	mGy/yr	mSv/yr	mGy/yr
~0	16.7	10.2	23.4	1,559
0.01	16.3	3.6	21.7	101
0.025	15.6	3.7	19.8	50.6
0.05	14.6	3.9	17.5	21.8
0.075	13.9	4	16.1	12.5
0.1	13.3	4	15	8.9

Table 4: Yearly radiation levels calculated for circular equatorial orbits at 500 and 600 km altitude. The rows are for tons of polyethylene shielding with the exception of the first row which calculated the radiation for one millionth of a gram of lunar regolith as a stand-in for no shielding at all (OLTARIS cannot calculate zero shielding levels). The columns are radiation levels at different altitudes and different measures. Note that even with essentially no shielding other than that likely from a space settlement hull (equivalent of 10 kg/m^2 of polyethylene), a 500 km orbit easily meets the limits. Note that the 6.6 mGy level is not met at 600 km with up to 100 kg/m^2 of shielding. Red indicates that the level roughly meets our 20 mSv/year limit (but not always the 6.6 mGy/year limit for pregnant women). All calculations by OLTARIS.

Table 4 suggests that for settlements in very low equatorial orbit (at 500 km), no shielding is required to meet the 20 mSv/year and only a small amount to meet the 6.6 mGy/year threshold. However, even the small amount of shielding provided by a pressure hull should be more than sufficient to meet the pregnant woman threshold.

Note the very high radiation level (mGy/year column) with no shielding at 600 km. This is mostly trapped protons that can be easily shielded as is seen from the rapid drop-off when small amounts of shielding are added. Also note that the mSv/year level is much smaller than the mGy/year level. This is because the mSv/year measurement is for the ovaries which are protected by the surrounding tissue whereas the mGy/year level is for a point protected only by the shielding.

The secondary radiation produced by the hull and interior materials may increase the radiation levels experienced, but that requires detailed knowledge of hull materials and thickness and an

understanding of the interior structures that is well beyond the scope of this paper. Fortunately, even with small amounts of shielding producing secondaries we are still below the 20 mSv/year and 6.6 mGy/year thresholds. There is, however, an interesting effect we can analyze.

The effect of secondary radiation can be seen in Table 5. Note that the small amount of shielding one might expect from settlement structure, atmosphere, interior buildings and so forth may actually increase the effective dose experienced with smaller levels of shielding, but stays below the 20 mSv/year threshold and below the radiation experienced with no shielding. Note that the hull and other materials may provide shielding the equivalent of 150 kg/m^2 to get below the 6.6 mGy/yr limit for pregnant women. However, the mGy/yr column is for a point protected only by shielding, but a fetus or embryo is also protected by the woman's body where the mSv/yr figures are 'measured' which is why they are so much lower than in the mGy/year column for small amounts of shielding.

shielding	600 km	
ton/m^2	mSv/yr	mGy/yr
~0	23.4	1,559
0.01	21.7	101
0.025	19.8	50.6
0.05	17.5	21.8
0.075	16.1	12.5
0.1	15	8.9
0.15	13.6	6.1
0.2	12.9	5.3
0.25	12.5	4.9
0.5	12.6	4.9
0.75	13.4	5.1
1	14.2	5.2
1.25	14.4	5.2
1.5	14.5	5.2
1.75	14.4	5.1
2	14.1	4.9

Table 5: Note the local minimum at 0.25 tons shielding and the local maximum at 1.5 tons, with radiation increasing between the two in the

mSv/yr column. The minimum is caused by blocking protons and the maximum by unabsorbed GCR secondary radiation which causes more damage than the primary particles. The first column is tons of polyethylene shielding per square meter at a 600 km circular equatorial orbit. Red indicates that the level roughly meets our 20 mSv/year threshold, but not necessarily the pregnancy limit. All calculations by OLTARIS.

Figure 1 illustrates the physics behind this effect.

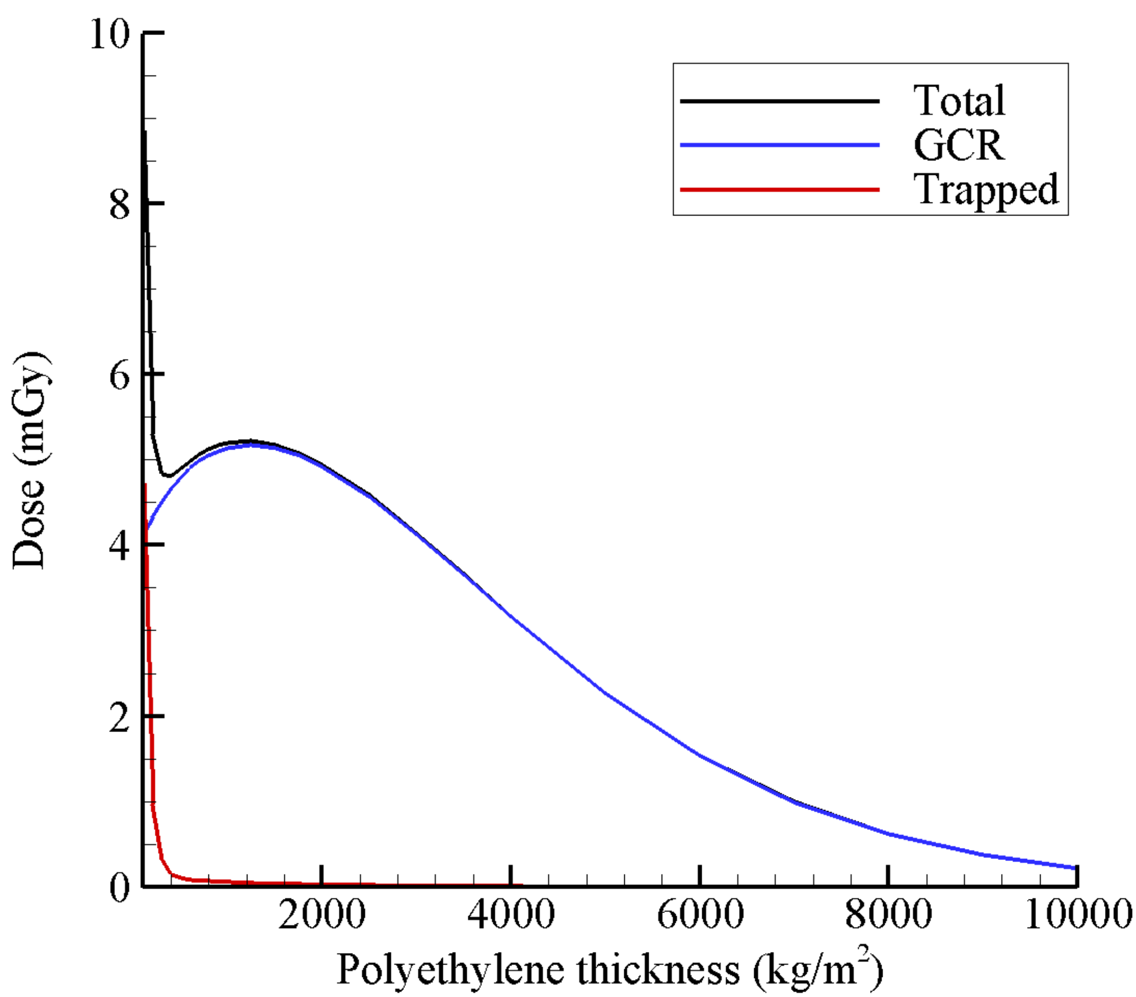

Figure 1: The trajectory was circular at 600 km and 0 degree inclination. The trapped proton component (red line on plot) consists mainly of lower energy protons that are

stopped with little shielding. The dose profile from this part of the environment falls off rapidly with depth as one might expect. Image credit NASA.

The GCR component (blue line on plot) consists of high energy protons, alpha particles, and heavy ions. However, the GCR in LEO is much different than in free space, especially at 0 degree inclination. At this low inclination, only the most energetic GCR make it through the geomagnetic field. These high energy particles initiate nuclear interactions in the shielding that produce secondary particles, leading to an increase in exposure. You can see the dose increases until around 1,500 kg/m^2, and gradually declines thereafter. This behavior is analogous to the so-called Pfotzer maximum observed in the Earth's atmosphere [Slaba 2014].

To understand the effect of inclination note that there is a region of high radiation near the equator called the South Atlantic Anomaly [Schimmerling] shown in Figure 2. The effect of inclination can be seen in Table 6, and it is dramatic: space settlements in inclined orbits require multiple tons of water shielding to meet the 20 mSv/year threshold even at fairly small inclinations. This is because equatorial orbits bypass most of the South Atlantic Anomaly. Clearly, from a radiation perspective, LEO settlements should be in equatorial orbits if at all possible.

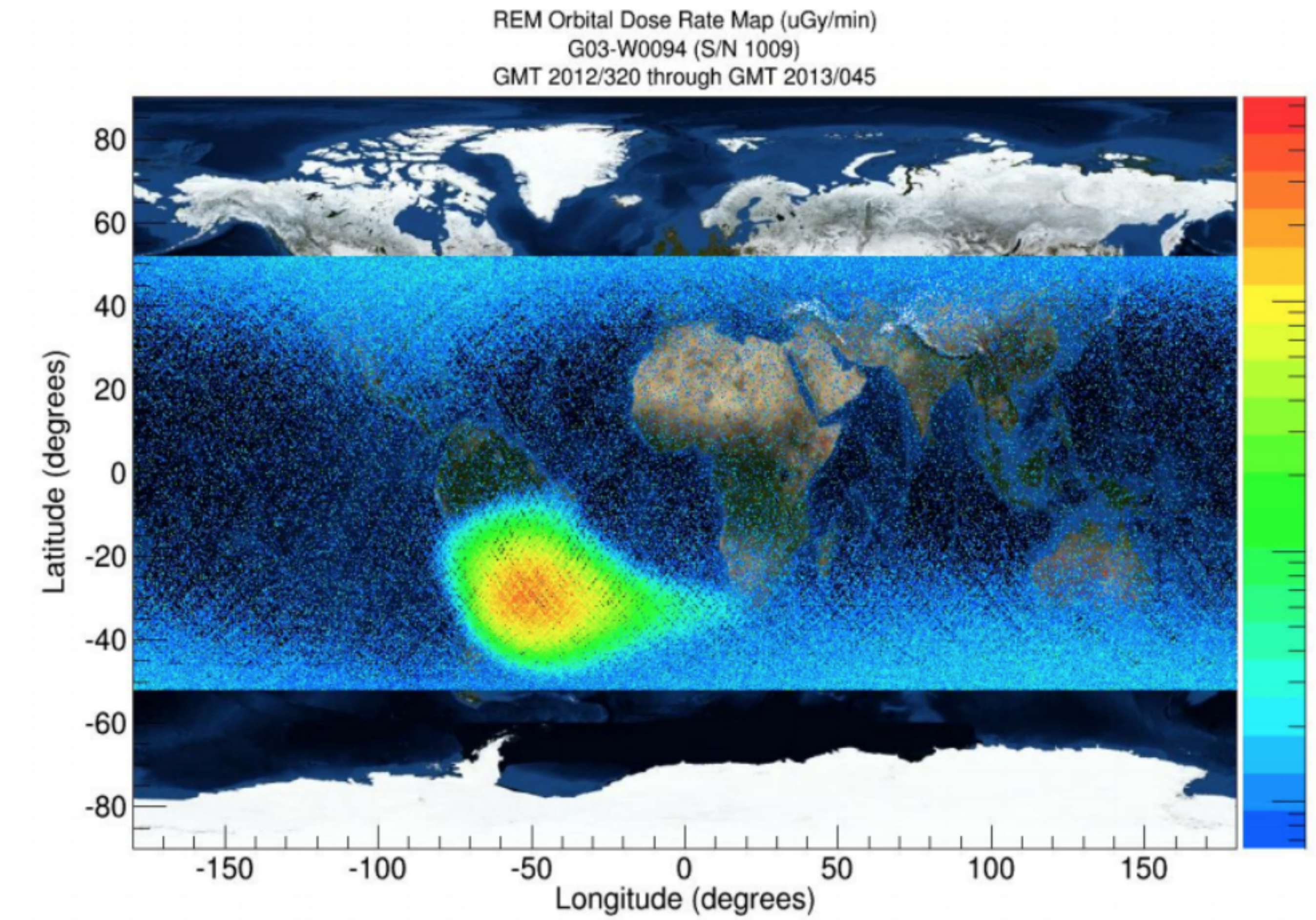

Figure 2: Radiation measurements taken on the ISS (International Space Station). Note the high levels of radiation over the South Atlantic and much of South America and very low levels near the equator. These low levels are well below our 6.6 mGy/yr threshold, but the ISS orbit is around 400 km, somewhat below the altitude of the computational data presented in the paper. Image credit NASA.

Mass (tons/m^2)	0° (mSv/yr)	15° (mSv/yr)	30° (mSv/yr)	45° (mSv/yr)	60° (mSv/yr)	75° (mSv/yr)	90° (mSv/yr)
0.25	14.6	262.8	636.0	424.1	345.0	335.5	334.0
0.5	12.1	112.1	253.5	178.2	164.0	168.7	170.3
1	13.2	43.4	88.7	79.1	90.3	100.2	102.7
2	14.0	21.6	36.7	45.5	58.9	66.4	68.3
3	12.6	16.4	25.1	33.2	42.4	47.1	48.3
4	10.3	12.3	17.6	23.5	29.4	32.2	32.9
5	7.9	8.9	12.1	16.1	19.6	21.3	21.7
6	5.7	6.3	8.2	10.7	12.7	13.7	13.9

Table 6. This shows the effect of inclination and shielding on radiation levels. The rows indicate the amount of radiation inside a settlement with the given amount of water shielding. The columns correspond to different orbital inclinations at a 600 km altitude. Red indicates that the level meets our 20 mSv/year threshold. The levels reported here are for human tissue in general, not human ovaries as in the other tables. Thus, the levels are not directly comparable to other tables in this paper but the differences are small. This measure is more optimistic as the ovaries are particularly vulnerable to radiation. Note that the other LEO tables use polyethylene and this uses water. All calculations by OLTARIS.

Method

All of the calculations in this paper were made with OLTARIS. Figure 3 indicates the parameters used for the LEO calculations (except Table 6). Only the material (the “sphere”) and the altitude were changed for each run. For this study, the model calculates radiation for a point in the middle of a sphere of uniform materials and also calculates the biological effect on the ovaries of a woman placed at this point. Figure 4 indicates the parameters used for the free space calculations. Only the material (the “sphere”) changed between runs. Calculation results were usually read off the OLTARIS output and entered by hand into a spreadsheet, but for Table 6 the “Copy Data” OLTARIS button was used. Except for Table 6, the mSv/year columns always came from the human ovaries results. The response function measured the dose in tissue using the “Computerized Anatomical Female (CAF)” model. The details of what these parameters mean can be found in the help and reference sections of the OLTARIS web site.

Project Name: poly600km0degree
Comments: [No Comment]
Project Environment:

Type:	Earth Circular Orbit
Comments:	*No Comments*
User-defined GCR	1977-06-27 to 1978-06-27 (mission duration = 365.0 days)
Altitude	600.0
Inclination	0.0
Components:	Galactic Cosmic Ray (GCR)? YES Trapped Protons? YES Neutron Albedo? YES
GCR Model:	BO-10
DSNE?	NO

Project Geometry:

Sphere Name poly0.01
Comments [No Comment]
Number of Layers: 1
Total thickness 10.0 kg/m2
Sphere Layers:

- polyethylene *10.0 kg/m2*

Enabled Response Functions: Dose in Tissue Effective Dose Equivalent(CAF)

FIRSTGOV Your First Click to the U.S. Government
+ Freedom of Information Act
+ NASA Privacy Statement, Disclaimer, and Accessibility Certification
NASA Official: Chris Sandridge
Project Manager: Lisa Simonsen
Website Manager: Jan Spangler
OLTARIS Last Modified on 07/30/2014
TARIS Fortran Code Rev. 3.4

Figure 3 shows the parameters used for the LEO calculations. Only the materials ("sphere name" which includes the thickness) and altitude changed between runs.

Project Name: FreeSpace
Comments: [No Comment]
Project Environment:

Type:	Free Space
Comments:	*No Comments*
GCR Model:	BO-10
Event	1977 Solar Min (DSNE) (mission duration = 365.0 days)

Project Geometry:

Sphere Name lunar10
Comments [No Comment]
Number of Layers: 1
Total thickness 10000.0 kg/m2
Sphere Layers:

- lunar_regolith_a17 *10000.0 kg/m2*

Enabled Response Functions: Dose in Tissue Effective Dose Equivalent(CAF)

FIRSTGOV Your First Click to the U.S. Government
+ Freedom of Information Act
+ NASA Privacy Statement, Disclaimer, and Accessibility Certification
NASA Official: Chris Sandridge
Project Manager: Lisa Simonsen
Website Manager: Jan Spangler
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Figure 4 shows the parameters used for the free space calculations. Only the materials ("sphere name" which includes the thickness) changed between runs.

Radiation in space varies with time. All of these calculations used the same one year time period during the 1977 Solar Minimum, which is a conservative choice for GCR levels as they tend to be high at solar minima. As cosmic radiation during minima is a factor of three or four higher than at maxima [Clement 2012], most other time periods would be expected to generate lower radiation figures.

Validating the Radiation Model and Thresholds

This study is based on the output of sophisticated radiation models developed by NASA and others. However, models are never completely accurate and the region of space we are interested in does not appear to have received extensive examination. Thus, it is possible the radiation model is not completely accurate.

The OLTARIS LEO radiation model is known to be somewhat inaccurate, and low, for trapped protons and electrons. However, these particles will likely be absorbed by the hull material needed to maintain atmospheric pressure and 1g centripetal force for artificial gravity. The particles of particular interest, relativistic heavy ions, are probably better modelled as the dynamics are much simpler. Existing archives should be examined for relevant data.

Nonetheless, since so much depends on the exact radiation levels it would be wise to send a small satellite with suitable sensors to the region, say a 450 km by 650 km elliptical orbit with zero inclination. It must have sensors to measure the flux of high energy, high mass particles (GCR) as these are the primary threat. If other sources of radiation can be measured as well (particularly high energy inner belt protons), so much the better.

Conversions of radiation levels to biological effect are much more error prone than the radiation levels themselves. Indeed, for the fetus and embryo it cannot be done at all with current knowledge [Valentine 2003]. Thus, a focused research effort to understand the biological effects of radiation in LEO equatorial orbits is in order, particularly for children and pregnant women. Preparatory work can be done on the ground, but it is impractical to reproduce the relevant radiation environment on Earth. Thus, spaceflight experiments are necessary. This should involve a small animal centrifuge in orbit to control for the effects of weightlessness.

The importance of understanding space relevant GCR doses is hard to overstate. The primary threat is these particles and their biological effect is poorly understood. Most animal studies assume that much higher doses for much shorter periods of time are equivalent to year or multi-year exposures, but that is not necessarily the case. Furthermore, settlers will be exposed not for years but for decades. Understanding these particles should be a primary focus of the proposed research program.

The same studies that examine biological effect can be used to help validate (or modify) the thresholds chosen (20 mSv/year for the general population and 6.6 mGy/year for pregnant women). While the adult general population level is very well supported, for children and

pregnant women the level will require a great to deal of research and will probably need modification. Thus, studies will need to include multi-generational work to look for problems during pregnancy.

The easiest way to conduct such studies is on the International Space Station (ISS), which is available today and can study rodents (among other animals). However, there is no small mammal centrifuge and the ISS radiation environment is much more extreme than in equatorial LEO as the ISS is in a 51.6 degree inclination orbit (see Table 6). If ISS studies suggest that the problems may be unacceptable, then a suitable biological research station in equatorial LEO will be necessary since the effects should be less given the much lower radiation levels found there.

Discussion

The primary interest of the authors is in space settlement. These radiation shielding findings, should they stand up to further investigation, have strong implications for the easiest path to the first settlements and how we might spread throughout the solar system. First we discuss the radiation limits chosen and then settlement mass implications.

20 mSv/year and 6.6 mGy/year Limits

While the 20 mSv/year to ovaries limit should be sufficient to avoid premature sterility there may be more severe than expected problems with birth defects, cancer, cardiovascular problems, central nervous system problems and/or cataracts, all of which can be affected by in-space radiation, although there is reason to believe ovaries are the most at risk. The 6.6 mGy/year limit for pregnant women is much more speculative, although it is well below the thresholds for severe damage observed in experiment and nuclear bomb survivors (see Table 1). Both thresholds are well below background radiation in some inhabited parts of Earth, but the nature of the space radiation threat, primarily high energy, heavy nuclei, is much different than the radiation these thresholds are based on.

However, even if issues arise they may not be sufficiently severe to deter a small fraction of Earth's population from moving into space settlements, and only a very small fraction of Earth's seven billion people are needed. The pull of space settlement can be very strong. For example, a recent call for volunteers for an extremely risky one-way Mars settlement plan reportedly received over 200,000 responses [Mars One 2014] with many respondents even paying a registration fee. Moving from place to place on Earth often involves a significant increase in risk, including background radiation levels, for a variety of reasons and people do it anyway. There is more to life than minimizing radiation exposure.

Also note that the first space settlement will almost certainly not be built for decades, and it is reasonable to expect that at least some of the problems that may arise from low dose continuous radiation exposure will become easily correctable on this time scale. For example, cataracts can be treated effectively today. For many, earlier cataract surgery than expected on

Earth may be of minor importance compared to living in space. Also, the risks from space radiation may be minor compared to other threats. All this suggests that thresholds in the neighborhood of 20 mSv/year for the general population and 6.6 mGy/year for pregnant women is adequate to protect inhabitants and allow settlement of the solar system.

Of course, significant additional research in the relevant environment is necessary before construction begins.

Settlement Mass

The result that no shielding material may be necessary for settlement in LEO equatorial orbit was surprising to the authors and has far reaching consequences because above the Earth's magnetic field radiation shielding is the vast majority of orbital settlement mass (see Table 7). The exact values in Table 7 are not particularly accurate. For example, the mass of interior furnishings is not included. However, the mass reductions are so enormous that even with inaccuracies it is clear that placing settlements in equatorial LEO requires far, far less materials than in free space.

name	structural mass (tons)	air mass (tons)	shielding mass (tons)	total/non-shielding
multiple dumbbells	75,000	37,000	9,900,000	89
multiple torus	100,000	10,400	9,700,000	89
banded torus	112,000	13,200	7,000,000	57
single torus	4,600	1,900	1,000,000	155
cylinder	775,000	299,000	19,400,000	19
sphere	64,600	35,200	3,300,000	34
dumbbell	400	200	1,400,000	2,334

Table 7: Mass estimates from [Johnson 1975] as a function of settlement shape. The vertical dimension is various possible shapes. The second through fourth column are the mass of the structure, air, and shielding respectively. The last column is the mass reduction factor achieved by eliminating shielding. For example, eliminating the shielding for the cylinder reduces total mass by a factor of 19[6].

With our radiation thresholds the assumption that space settlements need massive shielding requirements falls apart in LEO equatorial orbits. The reason the 1970s studies placed settlements at L5 was proximity to lunar materials which are energetically easier to launch than from Earth. However, eliminating the mass for radiation shielding and moving to LEO makes launching everything from Earth arguably as easy or easier than delivering a settlement worth of lunar materials to L5. Indeed, the energy advantage of Moon launch over Earth launch is about

[6] The reason the cylinder value is so low is that the cylinder is very large, with a population of 100,000. The other shapes have populations of 2,000-10,000.

a factor of 19[7], the same as the radiation shielding mass factor disadvantage for the cylinder in Table 7. This means that the total energy to launch an unshielded settlement from Earth to LEO is (very roughly) the same as the energy to launch the materials for a shielded settlement from the Moon to L5.

Moreover, if materials are launched from Earth, one can send exactly what is needed rather than gathering and processing bulk materials from the Moon, reducing the mass of materials launched even more. Compared to the 1970s studies, this also eliminates the entire extraterrestrial mining, processing and manufacturing infrastructure assumed to be necessary to build the first orbital settlements[8]. Taking extraterrestrial mining out of the critical path for the first settlement allows a much more incremental approach to settling the solar system.

With no extra shielding beyond the structure, furnishings and atmosphere, a settlement in LEO may be vulnerable to particularly large solar flares. Fortunately, at the highest flux levels these are relatively short, usually hours, and dangerous ones are rare [Cucinotta 2012] [Clement 2012]. In a settlement such as Kalpana One[9] [Globus 2007], a low-g cylindrical swimming pool around the axis of rotation can be used as a solar storm shelter. When a solar storm threatens, everyone has to go swimming for a few hours, with short breaks when the Earth is between the settlement and the Sun. The children, at least, should find this mandatory swim party quite acceptable!

Settlements in LEO will be subject to atmospheric drag and without reboost will eventually enter the atmosphere and impact the ground. Fortunately, using electric propulsion for reboost requires little mass due to the high propellant velocities (10s of km/sec). For example, at 20 km/sec propellant velocity the Kalpana One space settlement requires around 2.3 tons/year of reaction mass at 600 km, 8.5 tons/year at 550 km, and 18.7 tons/year at 500 km[10]. This activity does require a great deal of energy.

Heavy objects in the 500 km equatorial orbits take centuries to deorbit if abandoned, leaving ample time to deal with any such event. For example, using the Orbital Lifetime Calculator[11] and assuming a very lightweight settlement with no radiation shielding and a mass per drag area of 950 kg/m^2, deorbit time is about 195 years for an altitude of 500 km.

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[7] When measured by the square of delta-v and only a little higher when measured using the rocket equation assuming high ISP.

[8] This infrastructure is highly desirable later on as we spread throughout the solar system. Note that settlements in LEO may become an early and lucrative market for asteroidal and lunar materials in space.

[9] Kalpana one is a 325m long, 250 m radius cylindrical settlement design for a population of perhaps 3,000.

[10] Using the methodology and data at http://spacience.blogspot.com/2012/03/how-to-calculate-drag-in-leo-using.html

[11] http://www.lizard-tail.com/isana/lab/orbital_decay/ accessed on 15 August 2014.

Long Term Implications

The superiority of some asteroidal materials, heavy in carbon compounds and water, to lunar materials for free space settlement radiation shielding has implications to the paths for growth as we settle the solar system beyond LEO. Even in cis-lunar space the accessibility of some asteroids and the superior radiation shielding characteristics of asteroidal materials may make retrieved asteroids the preferred material source for cis-lunar radiation shielding above the Van Allen belts. The current project to retrieve a boulder off an asteroid would be of great value for this path.

For settlement of heliocentric orbits the obvious approach is to build settlements co-orbiting with asteroids that supply the materials for the settlement. In the long term settlements built co-orbiting with asteroids make the entire solar system available for settlement. This also means that generation ships to nearby stars do not need a habitable planet at their destination; just some space rocks will do.

Conclusion

The conclusions of this paper should be considered preliminary and subject to revision as more is learned about the human body's response to radiation, particularly low levels of GCR. This is particularly true with regard to pregnant women and children. Studies to resolve these issues are best conducted in equatorial LEO, and the ISS may be a "good enough" platform. There is also uncertainty in all models, including those used here, so a radiation measurement mission to equatorial LEO is in order. However, we believe our findings have a good chance of holding up under further examination.

First, it appears that 20 mSv/year and 6.6 mGr/year are reasonable thresholds for a space settlement's general population and pregnant women respectively. This is higher than the average background radiation experienced by most people on Earth, but there are many inhabited parts of the world where background radiation approaches or even exceeds this level.

Second, given these limits, space settlements in LEO circular equatorial orbits may not require any dedicated shielding at all. This has strong implications for the location of the first orbital space settlement which, contrary to previous belief, may be easier to build in equatorial LEO using only launch from Earth rather than depending on extraterrestrial mining, processing and manufacture for bulk materials. This is because of the shielding provided by Earth's magnetic field and by the Earth itself. Of course, a settlement in LEO is better positioned for commerce with Earth than settlements in higher orbits or on the Moon or Mars.

Finally, asteroidal materials -- from the right kinds of asteroids -- are superior to lunar regolith for radiation shielding. This may mean that retrieving asteroids into Earth orbit may be competitive

with launching regolith from the Moon for radiation shielding of settlements in cis-lunar space. Furthermore, asteroids are a ready source of materials for settlements in heliocentric orbits.

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